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Technical Report No. 1

TESTS WITH VARIABLE STRESS RATIOS IN THE PLASTIC RANGE

by

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DEPARTMENT OF CIVIL ENGINEERING

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NEW HAVEN, CONN.

April, 1956

Tests with Variable Stress Ratios in The Plastic Range*

By Aris Phillips (Yale University)

Abstract. In this paper we consider, for aluminum 2S-0, the fundamental assumptions on which the simple incremental theory of plasticity is based, as well as the over-all validity of this theory. As far as the fundamental assumptions are concerned we are able to show that, whereas the flow rule is valid even for extreme types of paths of loading, a generalized stress-strain curve does not exist. Thus, it becomes necessary to modify the theory, and it is shown that the modified theory is substantiated by our experiments. We also show that the flow rule of the simple theory of creep is valid.

INTRODUCTION

In a previous paper[1] it has been shown that for aluminum 2S-0, in tests with variable stress ratios, the flow rule of the simple incremental theory of plasticity is fairly well verified by experiments. In this paper we again consider aluminum 2S-0. First we give additional information on the validity of the flow rule of the simple incremental theory of plasticity. Next we consider the flow rule of the simple theory of creep. We then show that, for the material in question a generalized stress-strain curve does not exist, and accordingly it is necessary to modify the stress-strain relations of the simple

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*The results presented in this paper were obtained in the course of research sponsored by the Office of Naval Research.

1. Aris Phillips and L. Kaechele, J. Appl. Mech. 23, 43 (1956).

incremental theory of plasticity. Finally, we show how well this modified theory is substantiated by our test measurements.

DESCRIPTION OF THE TESTS

The tests with which the simple incremental theory of plasticity and the simple theory of creep are compared in this paper were made with thin-walled tubes of aluminum 2S-0 which were subjected to combined tension and torsion with variable stress ratios. Four series of tests were made (Series A, B, C, and G).

For the test series A and B the stresses were measured[2] by means of a specially constructed mechanical type strain gage. For the test series C and G the strains were measured[1] by SR-4 resistance strain gages. The accuracy of the mechanical gage was $\pm 2 \times 10^{-5}$ inches per inch for the axial strain, and $\pm 5 \times 10^{-5}$ inches per inch for the shearing strain. The accuracy of the SR-4 gages in the plastic range is better than 5% for strains less than 3000 microinches per inch, and better than 10% for strains between 3000 microinches per inch and 10,000 microinches per inch. A comparison of the accuracy of the SR-4 gages with the accuracy of the mechanical gages in these tests shows that the SR-4 gages are the more accurate ones for small and medium increments of strain. For example, for axial strain measurements the SR-4 gages have better accuracy than the mechanical gage for strain increments of 200 microinches per inch or less.

The load was applied by means of a testing machine of the deadweight type[2] which does not include any ball bearings. Thus, errors due to the ball bearing friction are eliminated. A testing machine of the deadweight type is preferable to one of the straining type, because the former one will not hide any time effects.

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2. Aris Phillips, J. Appl. Mech. 19, 496 (1952).

The material of the tubes was supplied in the annealed condition in tubular form with an internal diameter of 0.75 inches and a wall thickness of 0.25 inches. The finished specimens had an over-all length of 11 inches with an intermediate length of 6-3/4 inches of reduced wall thickness equal to 0.030 ± 0.001 inches for the test series A, B, and C, and to 0.050 ± 0.002 inches for the test series G. The internal diameter of the machined specimen was 0.78 inches. The wall thickness of the tubular specimen was measured by using a specially constructed apparatus[2]. The ratio of the wall thickness to diameter was selected so as to delay buckling as much as possible and at the same time to insure an essentially uniform stress distribution throughout the wall of the specimen. No difficulties because of buckling have been encountered.

Microscopic study of the material showed that the grains were equiaxed, with an average size of from 0.004 to 0.008 inches. Random orientation was indicated by random light reflection angles for different grains in the polished specimens.

As is to be expected with pure aluminum a considerable amount of creep occurs at the higher stress levels, although the rate of creep very soon becomes negligible for short time readings (of the order of a few minutes). If the load, however, is sustained for half an hour or more we shall have substantial creep strains. In a few cases, after the reading for the plastic strains had been made, we kept the load constant for a considerable time so that subsequent creep strain measurements could be made at room temperature. After a number of creep strain measurements, for the same load, had been made, the load was increased again so that new plastic strain measurements could be taken.

THE FLOW RULE

The simplest incremental theory of plasticity has the stress-plastic strain relations[3]

$$d\epsilon_x'' = \frac{F(\tau_o)}{3\tau_o}\left[\sigma_x - \frac{1}{2}(\sigma_y + \sigma_z)\right]d\tau_o\,,$$
$$d\gamma_{xy}'' = \frac{F(\tau_o)}{\tau_o}\tau_{xy}\,d\tau_o\,, \tag{1}$$

and the corresponding relations for $d\epsilon_y''$, $d\epsilon_z''$, $d\gamma_{yz}''$, $d\gamma_{zx}''$.

The octahedral shearing stress τ_o is given by

$$\tau_o = \frac{1}{3}\left[(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+6(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)\right]^{1/2}. \tag{2}$$

From equations (1) we find the proportionality relations

$$\frac{d\epsilon_x''}{\sigma_x-\frac{1}{2}(\sigma_y+\sigma_z)} = \frac{d\epsilon_y''}{\sigma_y-\frac{1}{2}(\sigma_x+\sigma_z)} = \frac{d\epsilon_z''}{\sigma_z-\frac{1}{2}(\sigma_x+\sigma_y)} =$$
$$= \frac{d\gamma_{xy}''}{3\tau_{xy}} = \frac{d\gamma_{yz}''}{3\tau_{yz}} = \frac{d\gamma_{zx}''}{3\tau_{zx}}\,, \tag{3}$$

which express the flow rule. Our first problem will be to find the degree of validity of the flow rule for the tests described.

In a tension-torsion test we have

$$\sigma_y = \sigma_z = \tau_{xz} = \tau_{yz} = 0 \tag{4}$$

Thus, relations (3) give

$$\frac{\sigma_x}{\sqrt{3}\,\tau_{xy}} = \frac{\sqrt{3}\,d\epsilon_x''}{d\gamma_{xy}''} \tag{5}$$

Hence if we superimpose a $(\sqrt{3}\,\epsilon_x'', \gamma_{xy}'')$ plane on the $(\sigma_x, \sqrt{3}\,\tau_{xy})$ plane, the vectors

3. Aris Phillips, Introduction to Plasticity (The Ronald Press Company, New York, 1956) p. 125.

$(\sqrt{3}\,d\epsilon_x'', d\gamma_{xy}'')$ with the points of application $(\sigma_x, \sqrt{3}\,\tau_{xy})$ will be directed radially outward from the origin. This is a criterion of the validity of the proportionality expressed by equations (3). A similar representation of the results of combined stress tests has been given by Hohenemser and Prager[4].

In Fig. 1 we see the results of three of the tests (B-4, B-8, G-1) concerning the validity of flow rule (3). In test B-8 the specimen was loaded first in tension and then in torsion, while the tensile stress was kept constant. In test G-1 the loading process was considerably more complicated. It is seen that in test G-1 we loaded first in tension and then in torsion while the tensile stress was kept constant; afterwards, the loading process consisted in either increasing τ while decreasing σ , or increasing σ while decreasing τ . We tried to make the reversals from increasing σ to decreasing σ and vice versa as sharp as possible without introducing unloading or neutral change of stress*. Such sharp reversals would show whether the direction of the strain increment is independent of the direction of loading. Test B-4 is intermediate to tests B-8 and G-1 as far as severity of the loading path is concerned.

From Fig. 1 we see that the flow rule is valid with good accuracy in all three tests. That the results of test G-1 satisfy the flow rule is quite remarkable, since recently published test results by Naghdi and his co-workers[5], with paths of loading similar to G-1, do not satisfy the flow rule.

In Fig. 2 we see the results of test C-2 in which the specimen was loaded first in torsion, and then in tension while the shearing stress was kept constant. From this figure we see that the flow rule is valid in the beginning,

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* For the definition of neutral change of stress, see Ref. 3, p. 124.

4. K. Hohenemser and W. Prager, ZAMM 12, 1 (1932).

5. P. M. Naghdi, J. C. Rowley, and C. W. Beadle, J. Appl. Mech. 22, 416 (1955).

and then an instability in the directions of the strain-increment vectors occurs. This instability may be due to the existence of corners in the yield surface. Such yield corners have been repeatedly discussed in the literature[6,7].

In some of the tests we tried to see whether at a given point of the loading path the direction of the strain increment vector will remain the same while creep deformation occurs. Fig. 3 shows the results. In all the tests in which the gradually increasing creep deformation has been measured, no change in the direction of the strain increment vector was detected. This shows that the flow rule is valid also during creep. It is interesting that in test C-2 instability in the direction of the strain increment vector occurs in plasticity and not in creep; hence this instability cannot be attributed to creep.

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6. D. C. Drucker, Proc. 1st U. S. Natl. Congress of Applied Mechanics, ASME (1951), p. 487.

7. D. C. Drucker and F. D. Stockton, Proc. SESA, 10, 2, p. 127 (1953).

COMPARISON OF THEORY WITH EXPERIMENTS

We now turn our attention to the function F in equations (1). Using equations (1) we calculate the quantity

$$d\Gamma_0'' = \frac{2}{\sqrt{3}}\left[d\epsilon_x''^2 + d\epsilon_y''^2 + d\epsilon_z''^2 + \frac{1}{2}\left(d\gamma_{xy}''^2 + d\gamma_{yz}''^2 + d\gamma_{zx}''^2\right)\right]^{1/2} \qquad (6)$$

We find

$$d\Gamma_0'' = F(\tau_0)d\tau_0 \qquad (7)$$

which, after integration becomes

$$\Gamma_0'' = \int F(\tau_0)d\tau_0 = f(\tau_0) \qquad (8)$$

In Figures 4, 5, and 6 we give the $\tau_0 - \Gamma_0''$ curves for the tests of the series A, B, and C. We see that there is a substantial disagreement between the $\tau_0 - \Gamma_0''$ curves of the various tests. Hence, a generalized stress-strain curve does not exist for the material in question. This disagreement, however, is of no basic importance for the validity of equations (1), because in these equations there enters only the slope $d\Gamma_0''/d\tau_0$ of the curves. From an inspection of the curves in Figures 4 to 6 it becomes obvious that for the same τ_0 the value of the slope $d\Gamma_0''/d\tau_0$ changes very much from test to test. Thus, the slope $d\Gamma_0''/d\tau_0$ could not be a function of τ_0. On the other hand, for the same Γ_0'' the value of the slope changes much less. Hence, we can consider $d\Gamma_0''/d\tau_0$ a function rather of Γ_0'' than of τ_0.

We found, however, that for values of Γ_0'' larger than about 2000 micro-inches per inch the $d\tau_0/d\Gamma_0''$, Γ_0'' curves are much closer to each other percentagewise than are the $d\Gamma_0''/d\tau_0$, Γ_0'' curves. This is due to the fact that $d\tau_0/d\Gamma_0''$ and $d\Gamma_0''/d\tau_0$ are equal to $\tan\alpha$ and $\cot\alpha$, respectively, where α is the angle which the tangent to the τ_0, Γ_0'' curve is making with the Γ_0'' curve. These trigonometric functions are sensitive to changes in the value of α, and $\tan\alpha$ is more sensitive for larger values of α than for smaller values; whereas for $\cot\alpha$ the opposite is true. Now, for an increasing Γ_0'' the angle α decreases and therefore $d\tau_0/d\Gamma_0'' = \tan\alpha$ becomes gradually less sensitive to the changes of the angle α, whereas $d\Gamma_0''/d\tau_0 = \cot\alpha$ becomes gradually more sensitive to the changes of α.

In Figures 7, 8, and 9 we see the $d\tau_0/d\Gamma_0''$, Γ_0'' curves for the test series A, B, and C. We see that these curves are close to each other for values of Γ_0'' larger than about 2000 microinches per inch. Assume now that we disregard the difference between the various $d\tau_0/d\Gamma_0''$, Γ_0'' curves, thus considering that $d\tau_0/d\Gamma_0''$ is a unique function of Γ_0'' for all the tests. Then

$$d\tau_0 = \varphi(\Gamma_0'')\,d\Gamma_0'' \tag{9}$$

and, integrating, we find

$$\tau_0 - A = \Phi(\Gamma_0''), \tag{10}$$

where A is an integration constant. Solving this equation for Γ_0'' we find

$$\Gamma_0'' = \psi(\tau_0 - A). \tag{11}$$

From equations (9) and (11) we then find

$$\frac{d\tau_0}{d\Gamma_0''} = \varphi(\psi(\tau_0 - A)) = \Psi(\tau_0 - A) \tag{12}$$

Thus, the assumption that $d\tau_0/d\Gamma_0''$ is a unique function of Γ_0'' is equivalent to the assumption that $d\tau_0/d\Gamma_0''$ is a unique function of $\tau_0 - A$ where A is a constant varying from test to test.

The stress-strain relations (1) will now be modified so that $d\tau_0/d\Gamma_0''$ will be considered as a function of Γ_0''. Thus we shall take into account the fact that the constant A changes from test to test, but we shall disregard the fact that the angle α varies from curve to curve for the same Γ_0'.

Let us denote with $\varphi(\Gamma_0'')$ the curve $d\tau_0/d\Gamma_0''$, Γ_0''. Then from expressions (3) which have been proved to be correct in the previous section we find

$$\frac{d\varepsilon_x''}{\sigma_x - \frac{1}{2}(\sigma_y + \sigma_z)} = \frac{d\Gamma_0''}{3\tau_0} = \frac{d\Gamma_0''}{d\tau_0}\frac{d\tau_0}{3\tau_0} = \frac{d\tau_0}{3\tau_0\cdot\varphi(\Gamma_0'')} \tag{13}$$

from which again it follows that

$$d\varepsilon_x'' = \frac{1}{3\tau_0\cdot\varphi(\Gamma_0'')}\left[\sigma_x - \frac{1}{2}(\sigma_y + \sigma_z)\right]d\tau_0. \tag{14}$$

Similarly we find

$$d\gamma_{xy}'' = \frac{1}{\tau_0\cdot\varphi(\Gamma_0'')}\,\tau_{xy}\,d\tau_0\,, \tag{15}$$

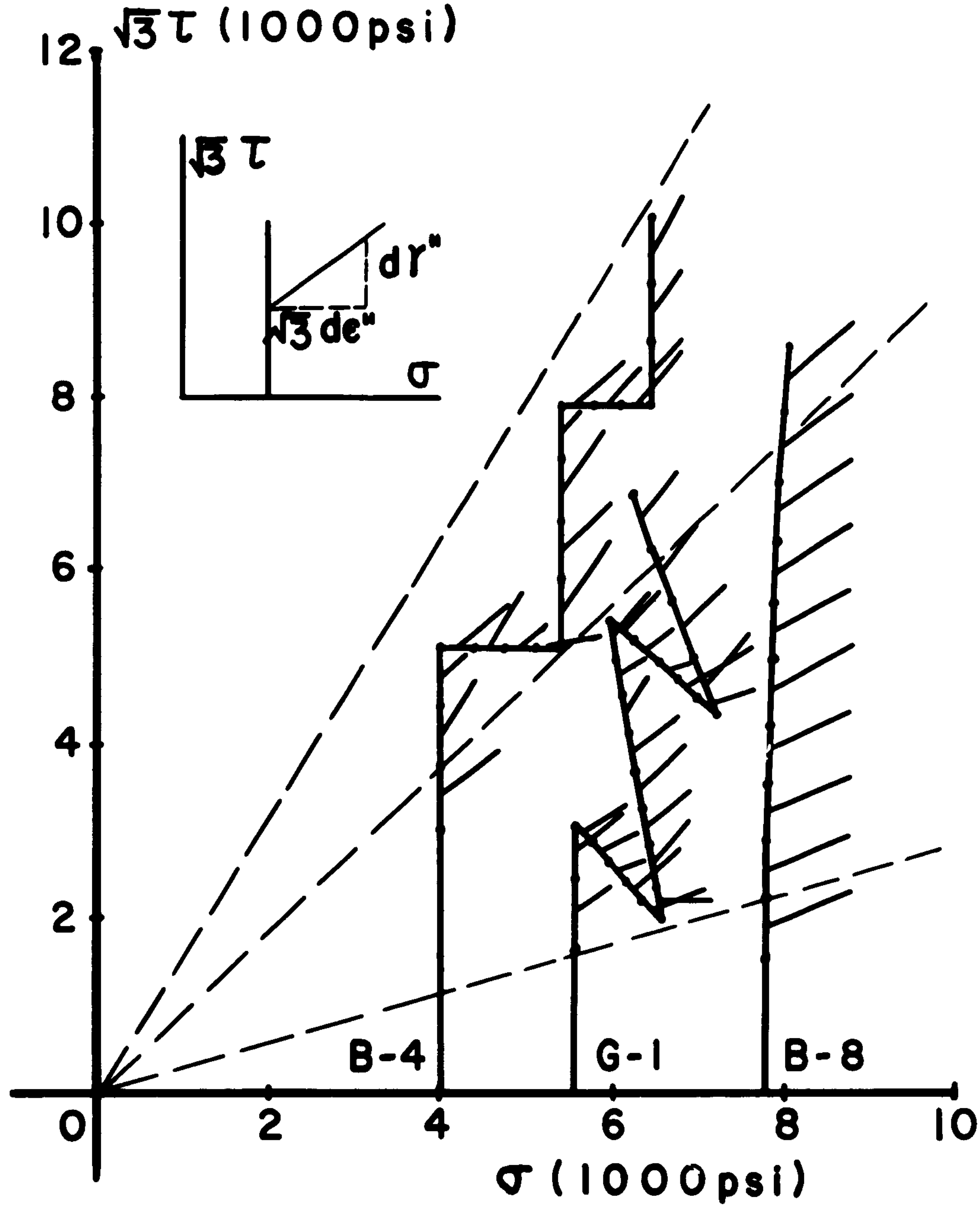
and the corresponding relations for $d\varepsilon_y''$, $d\varepsilon_z''$, $d\varepsilon_{yz}''$, and $d\varepsilon_{xz}'$. These are the modified stress-strain relations of the simple incremental theory of plasticity.

For a comparison of this modified theory with the tests, we determine $d\tau_0/d\Gamma_0''$ for each of the tests as a function of Γ_0'. Then we average these functions for the same Γ_0'', and this average is used as the $\varphi(\Gamma_0'')$ curve in equations (14) and (15).

In Figures 10 to 14 we compare some of our experimental results with theoretically calculated curves. We see that the theoretical calculations reproduce the experimental results with fair to good accuracy. We remark also that a substantial portion of the difference between theoretical and experimental curves occurs in the initial simple tension stage of the tests. This means that the difference between theory and experiment is due to a substantial part to the difference in the stress-strain curves in simple tension of the various specimens. Any possible lack of validity of the combined stress theory does not seem to be a more important factor in the difference between theoretical and experimental results than the factor just mentioned.

ACKNOWLEDGMENTS

The author wishes to thank Mr. V. Neubert for making the computations upon which this paper is based.



$\sqrt{3}\tau$ (1000psi)
12
10
8
6
4
2
0
2
4
6
8
10
σ (1000psi)
$\sqrt{3}\tau$
$d\gamma''$
$\sqrt{3}\,de''$
σ
B-4
G-1
B-8

Fig. 1

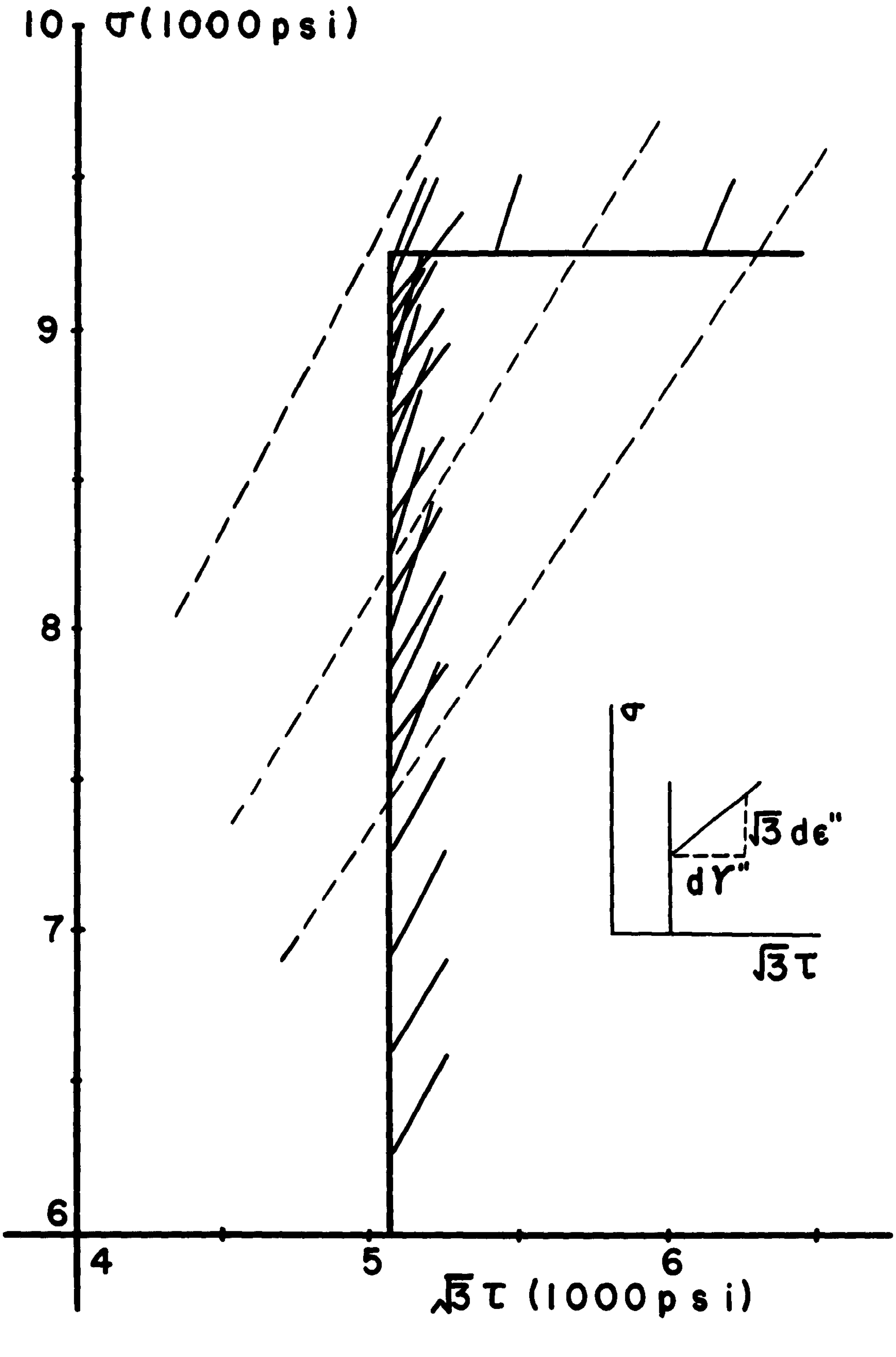
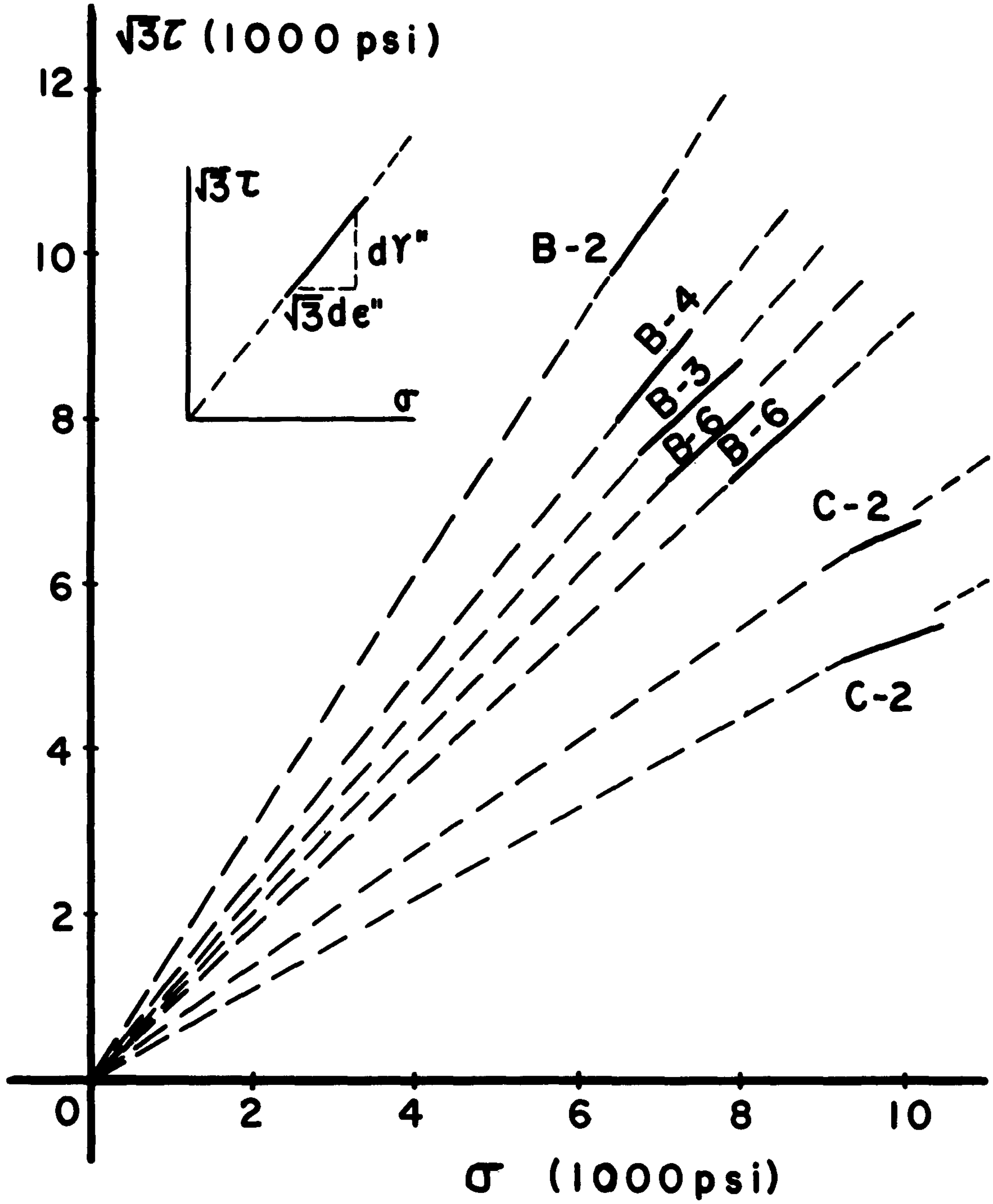


Fig. 2



$\sqrt{3}\tau$ (1000 psi)
12
10
8
6
4
2
0
2
4
6
8
10
σ (1000psi)
$\sqrt{3}\tau$
$d\gamma''$
$\sqrt{3}de''$
σ
B-2
B-4
B-3
B-6
B-6
C-2
C-2

Fig. 3

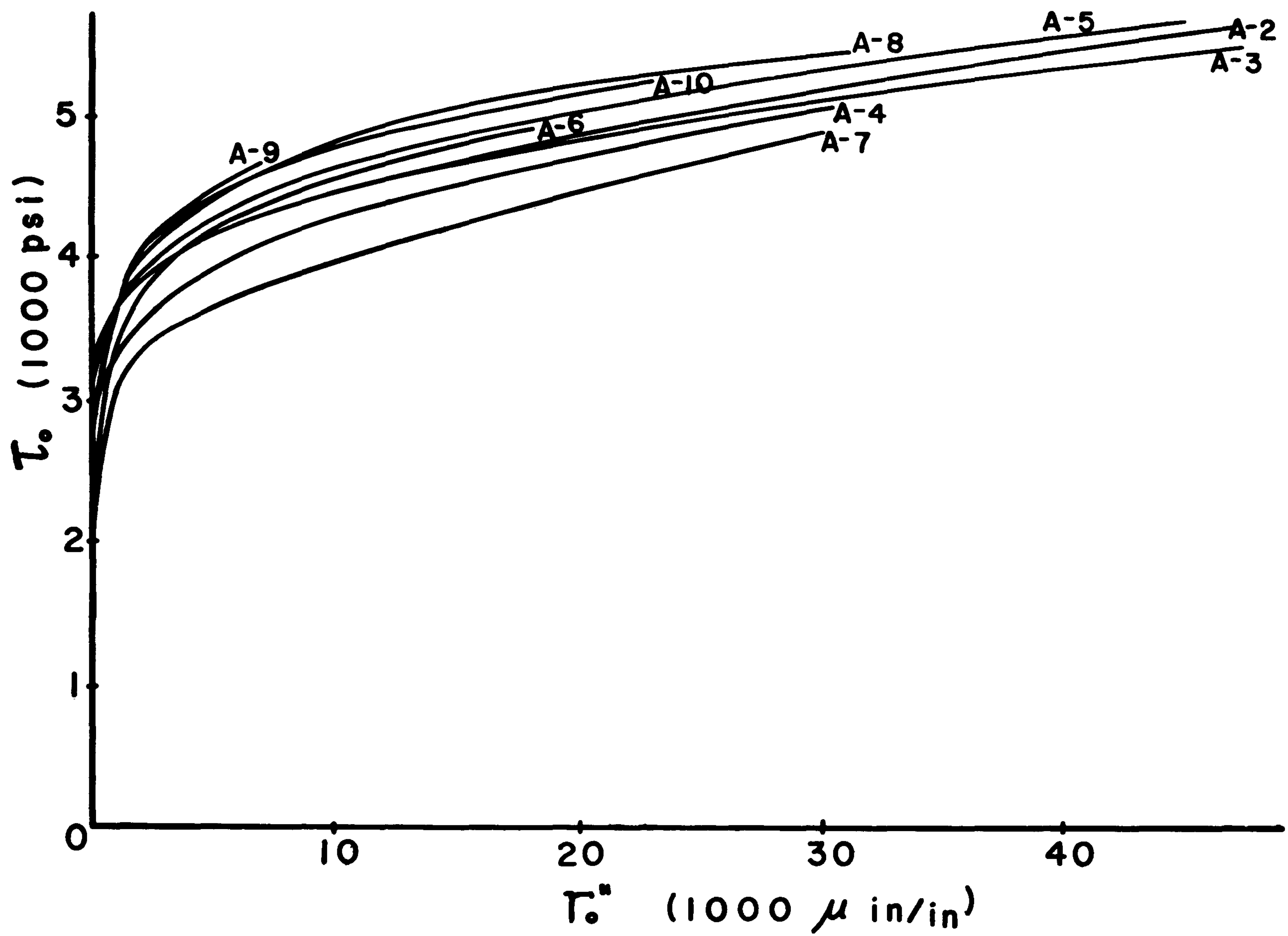

A-5
A-2
A-8
A-3
A-10
A-4
A-6
A-9
A-7
5
4
3
2
1
0
10
20
30
40
τ_o (1000 psi)
Γ_o'' (1000 μ in/in)

Fig. 4

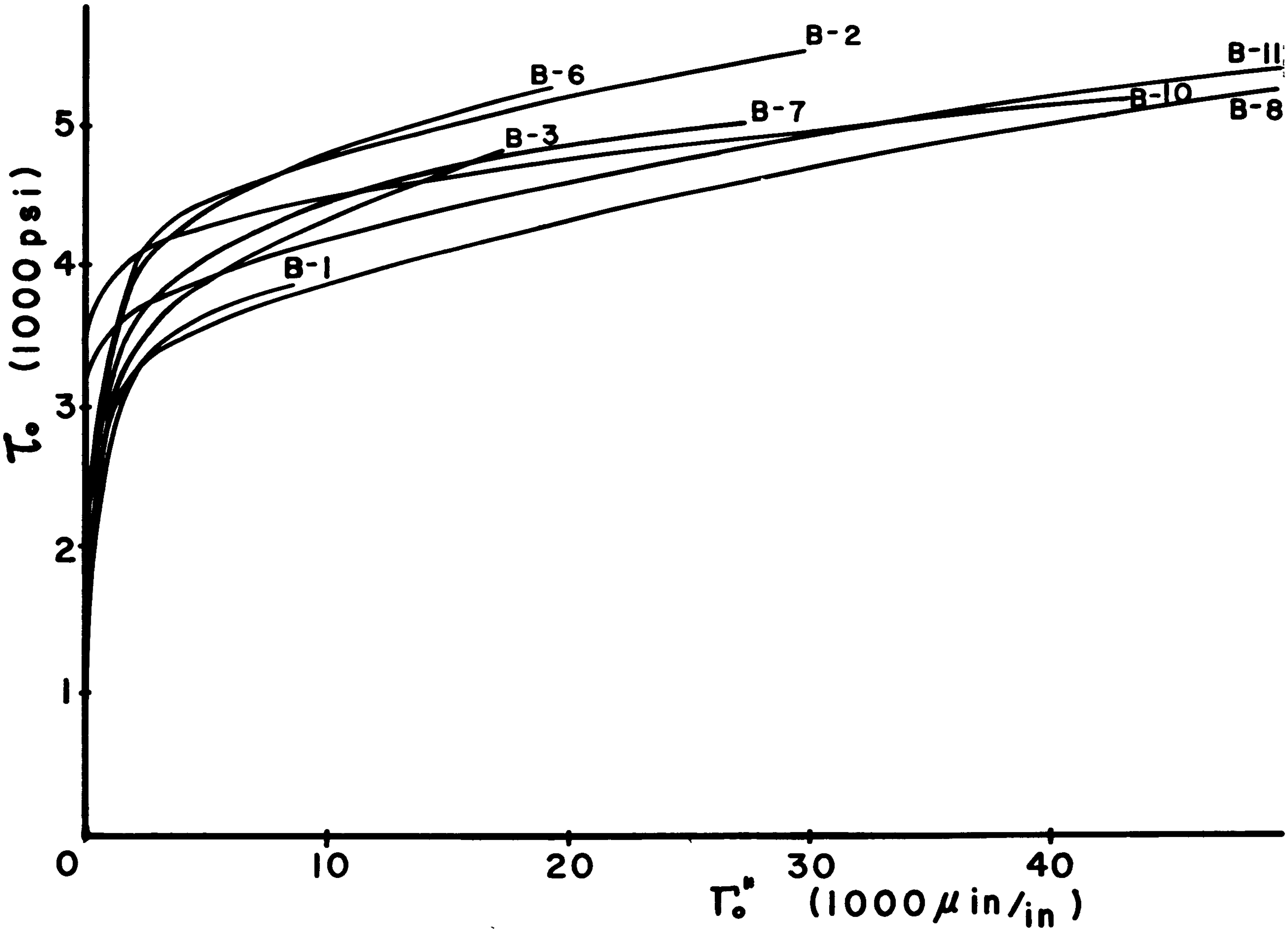

B-2
B-6
B-11
B-10
B-7
B-8
B-3
B-1
5
4
3
2
1
0
10
20
30
40
τ_o (1000 psi)
Γ_o'' (1000 μin/in)

Fig. 5

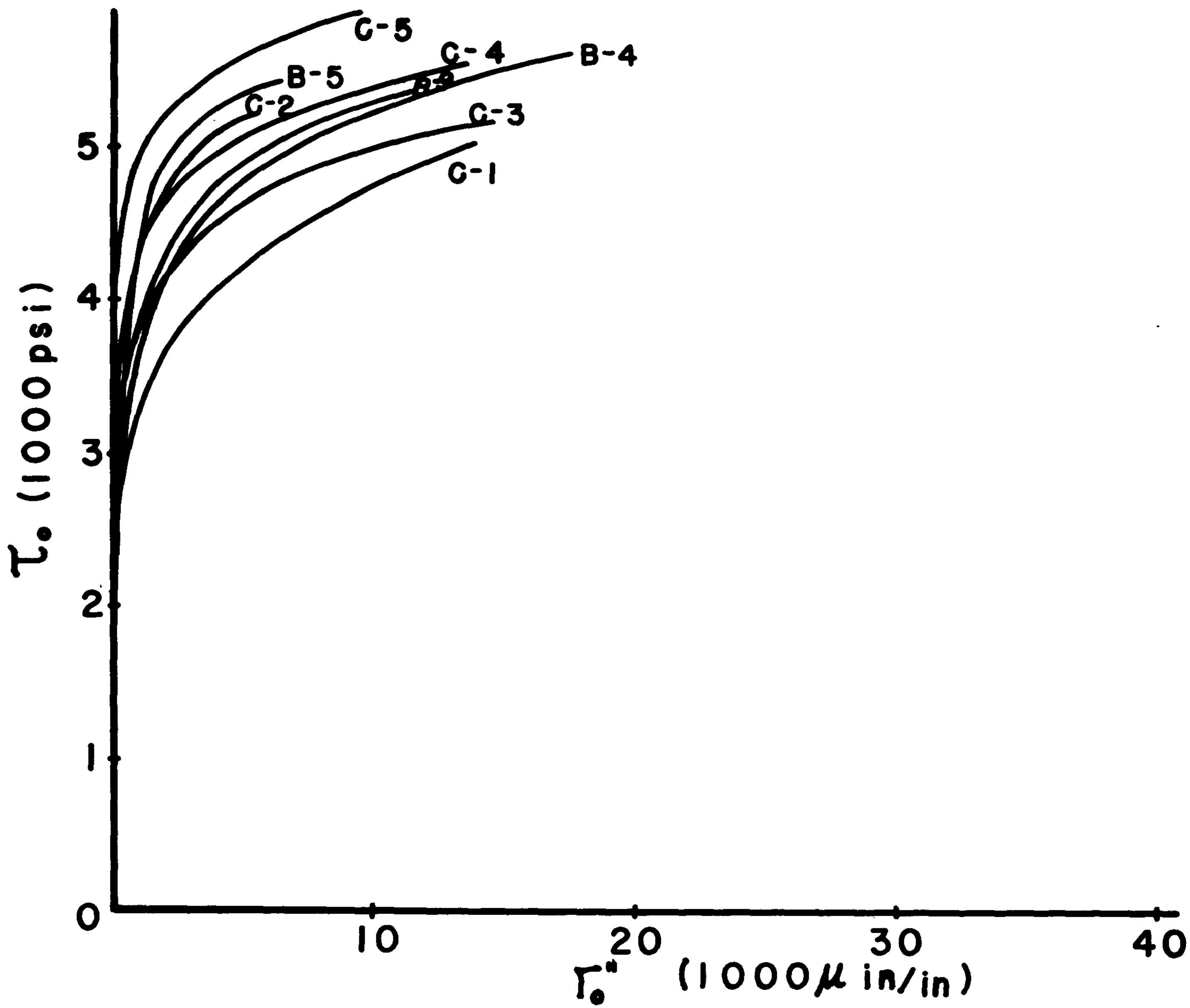
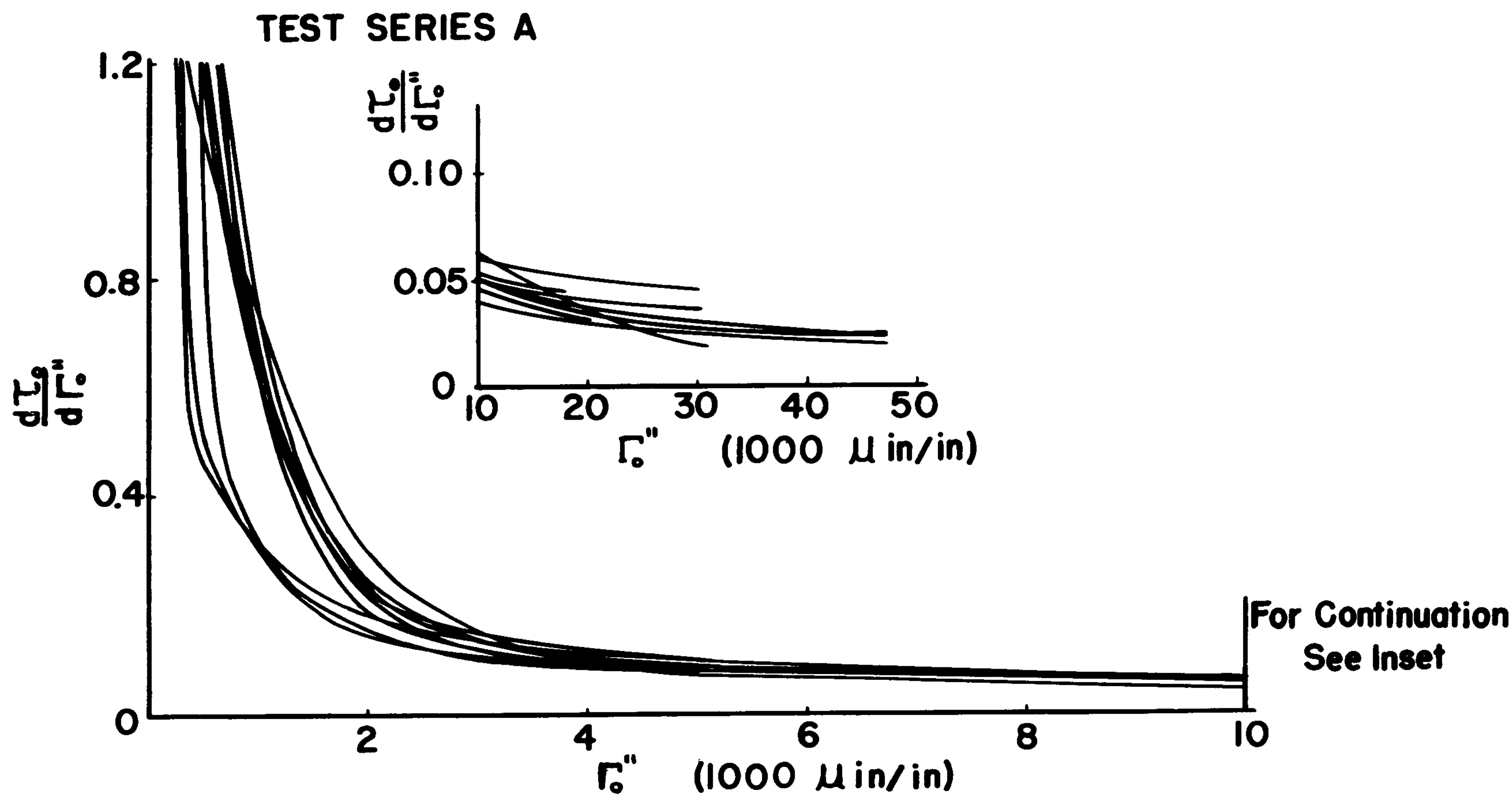

C-5
C-4
B-4
B-5
C-2
B-3
C-3
C-1
5
4
3
2
1
0
10
20
30
40
τ_o (1000 psi)
Γ_o'' (1000μ in/in)

Fig. 6



TEST SERIES A
$\frac{d\tau_o}{d\Gamma_o''}$
1.2
0.8
0.4
0
2
4
6
8
10
Γ_o'' (1000 μ in/in)
0.10
0.05
10
20
30
40
50
For Continuation
See Inset

Fig. 7

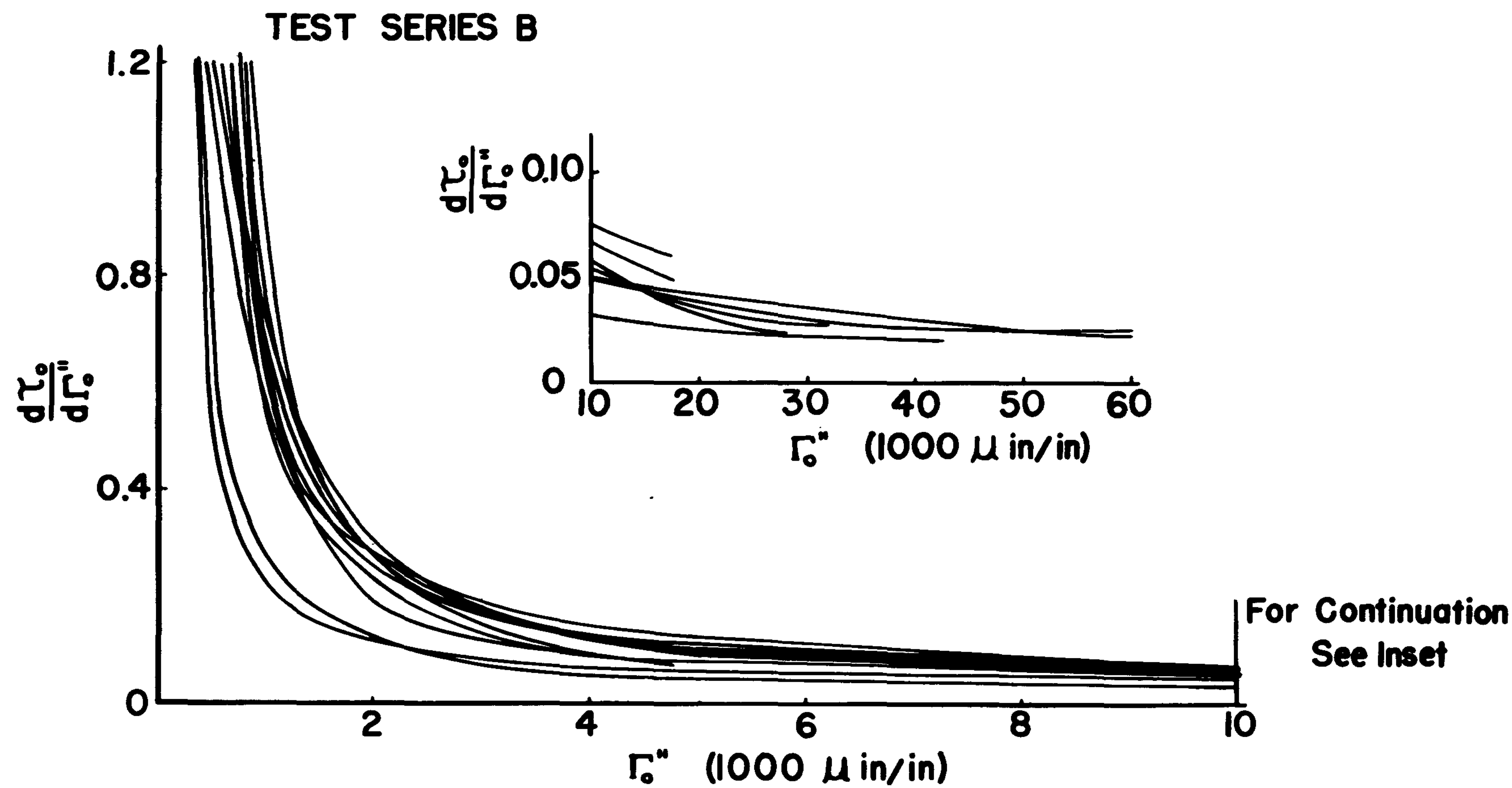

TEST SERIES B
1.2
0.8
0.4
0
2
4
6
8
10
$\frac{d\tau_o}{d\Gamma_o''}$
Γ_o'' (1000 μ in/in)
For Continuation
See Inset
0.10
0.05
0
10
20
30
40
50
60
$\frac{d\tau_o}{d\Gamma_o''}$
Γ_o'' (1000 μ in/in)

Fig. 8

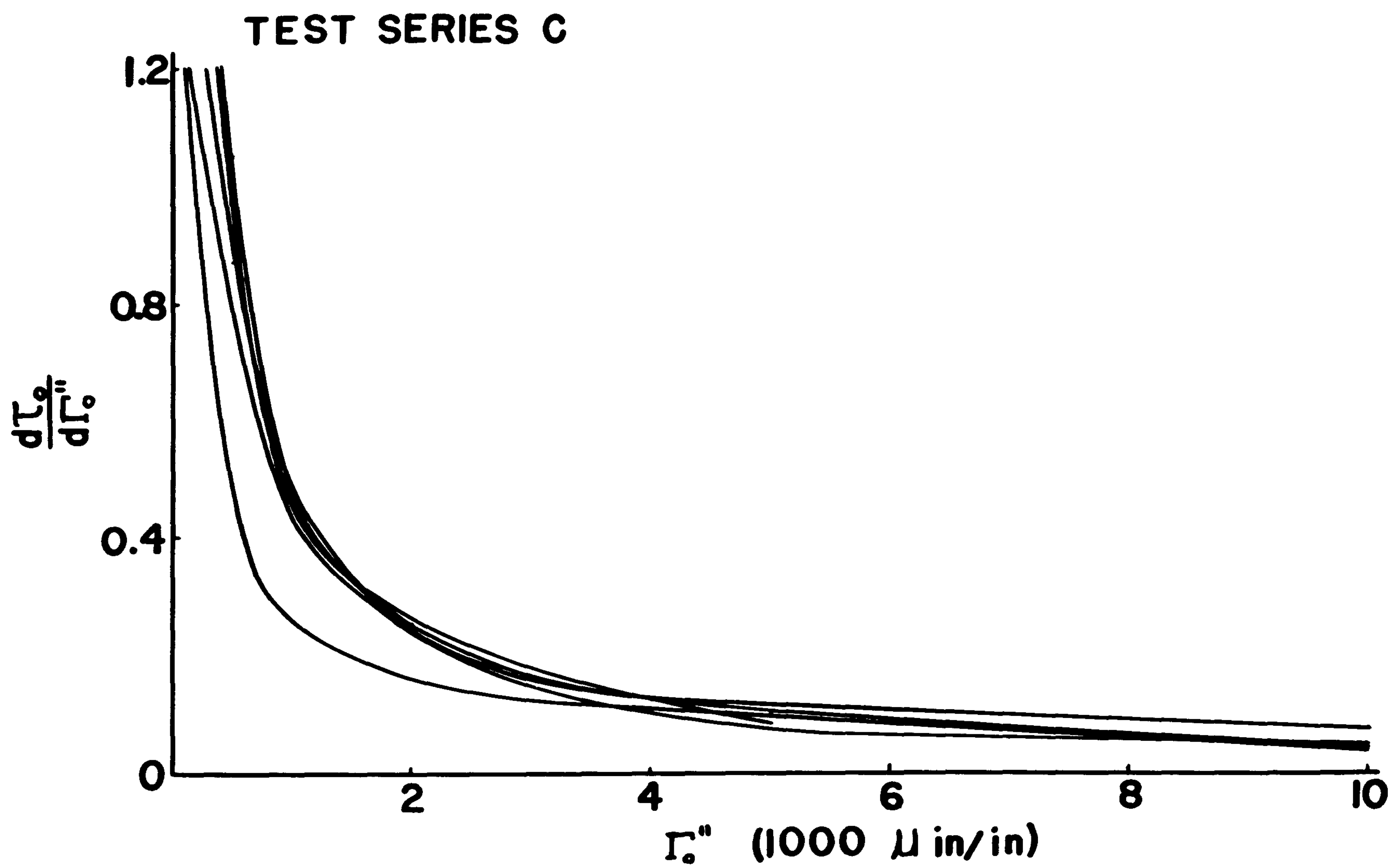

TEST SERIES C
1.2
0.8
0.4
0
$\frac{d\tau_o}{d\Gamma_o''}$
2
4
6
8
10
Γ_o'' (1000 μ in/in)

Fig. 9

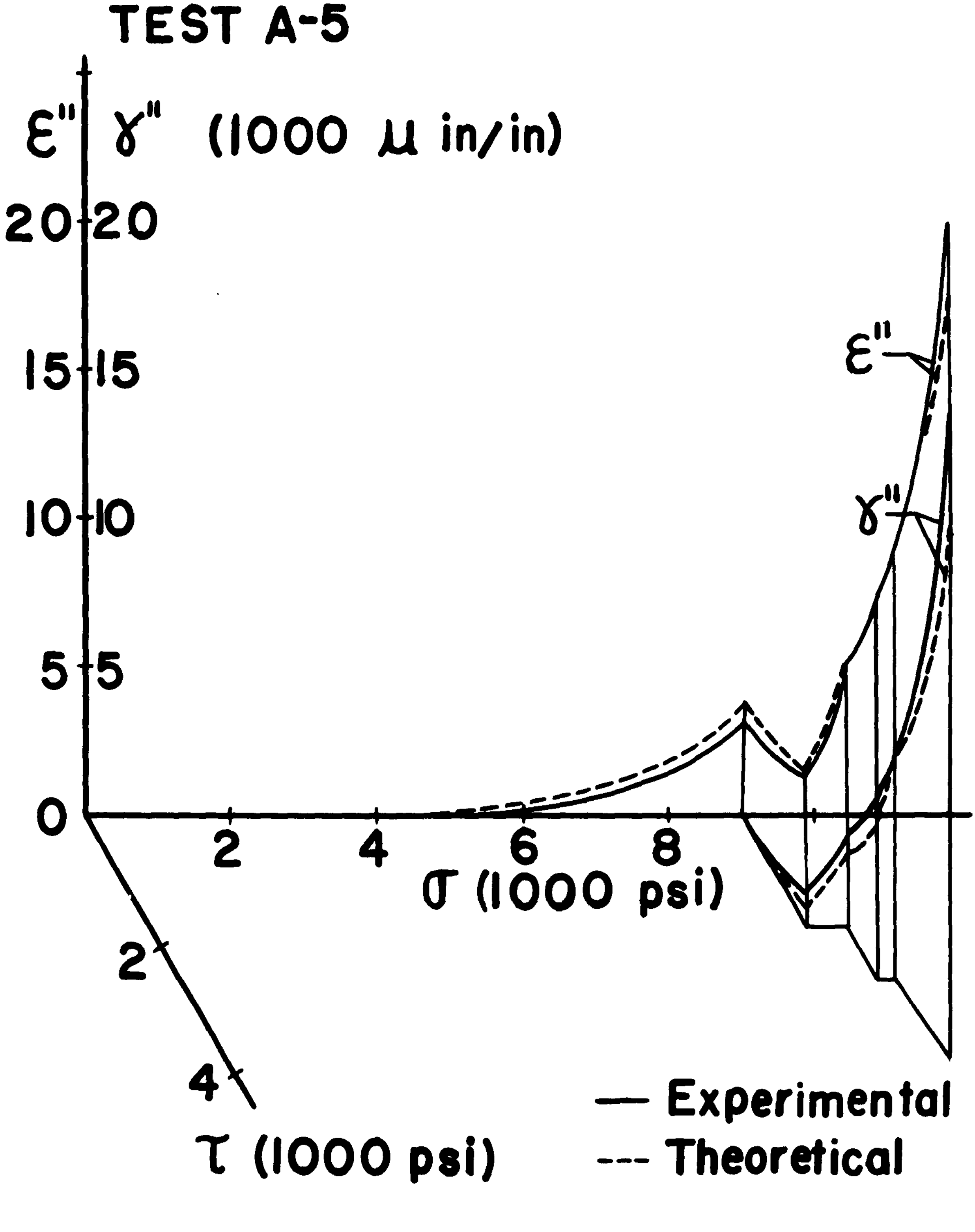

TEST A-5
ε'' γ'' (1000 μ in/in)
20 20
15 15
10 10
5 5
0
2
4
6
8
σ (1000 psi)
2
4
τ (1000 psi)
ε''
γ''
— Experimental
--- Theoretical

Fig. 10

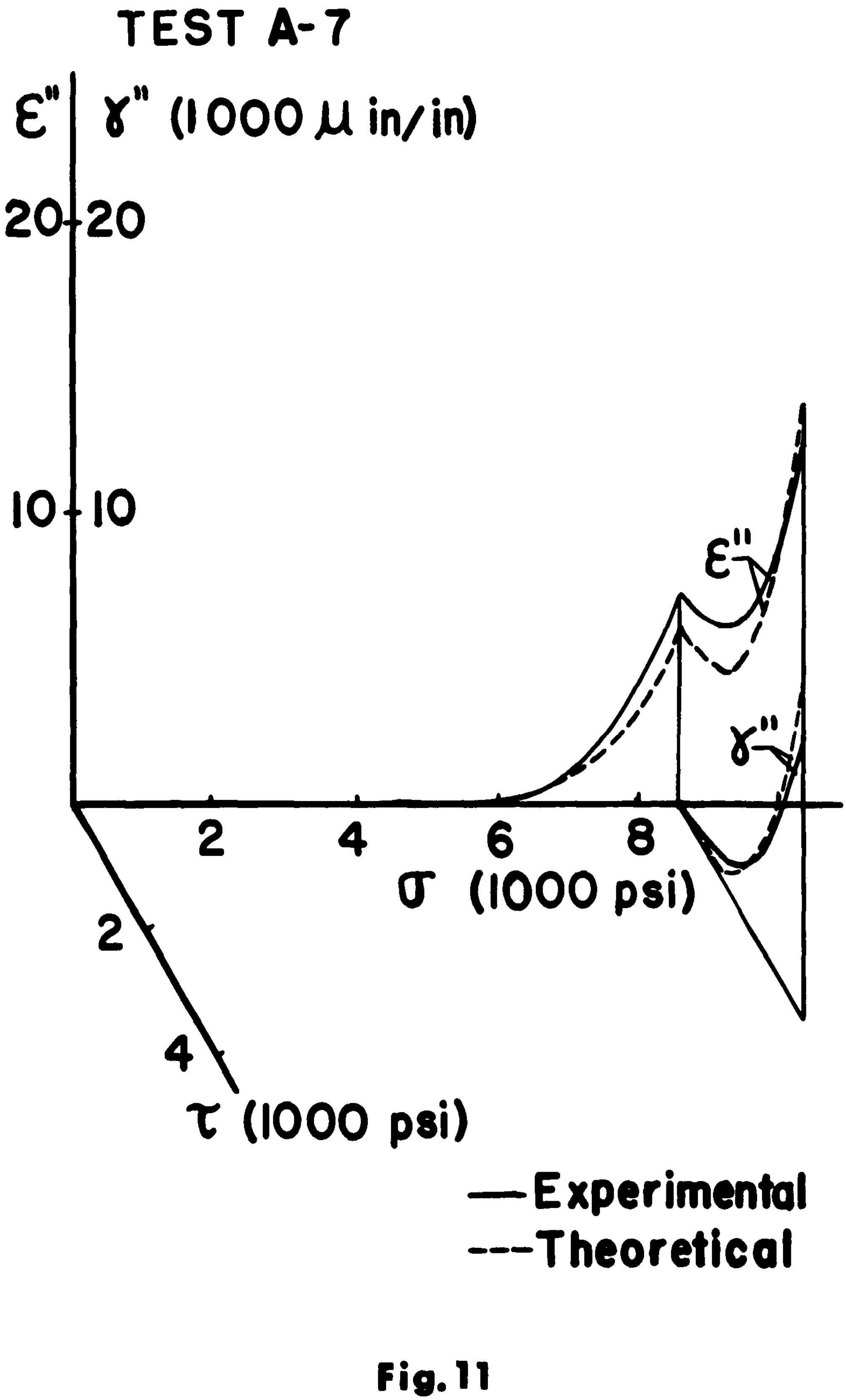
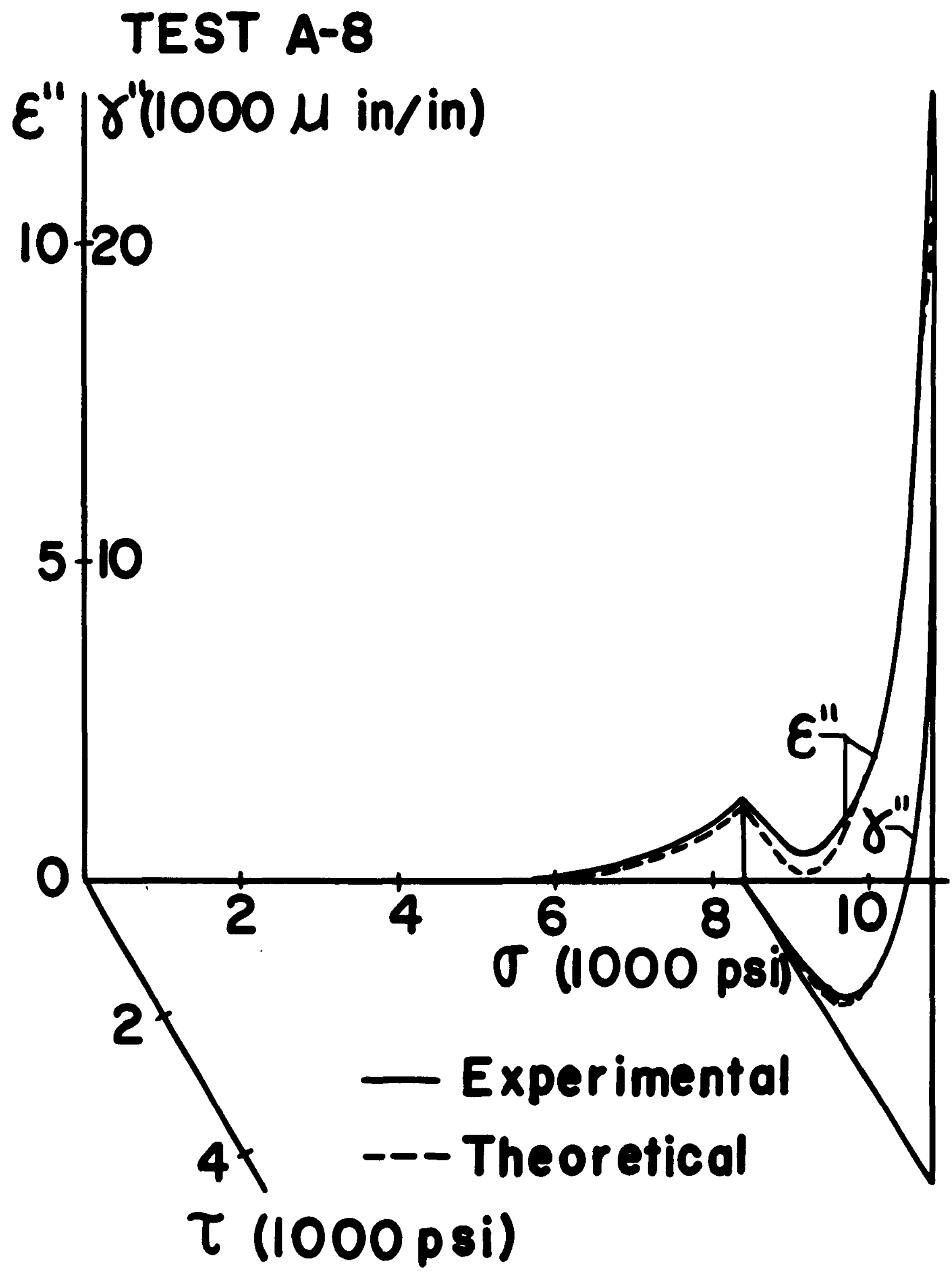

TEST A-7
ε" | γ" (1000 μ in/in)
20
20
10
10
2
4
6
8
σ (1000 psi)
2
4
τ (1000 psi)
ε"
γ"
—Experimental
---Theoretical

Fig. 11



TEST A-8
ε'' | γ'' (1000 μ in/in)
10
20
5
10
0
2
4
6
8
10
σ (1000 psi)
ε''
γ''
2
4
τ (1000 psi)
Experimental
Theoretical

Fig. 12

TEST B-2

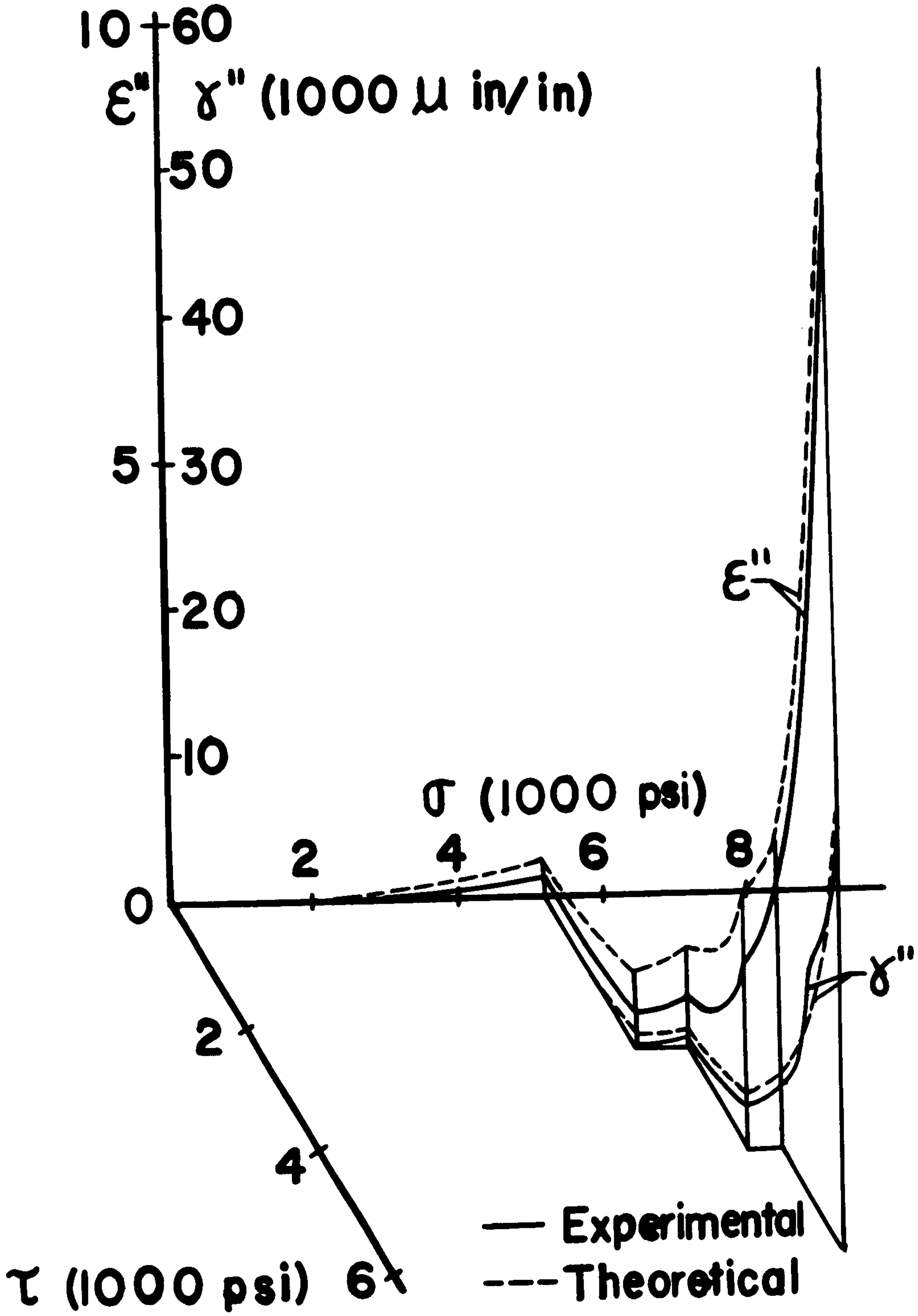


Fig. 13

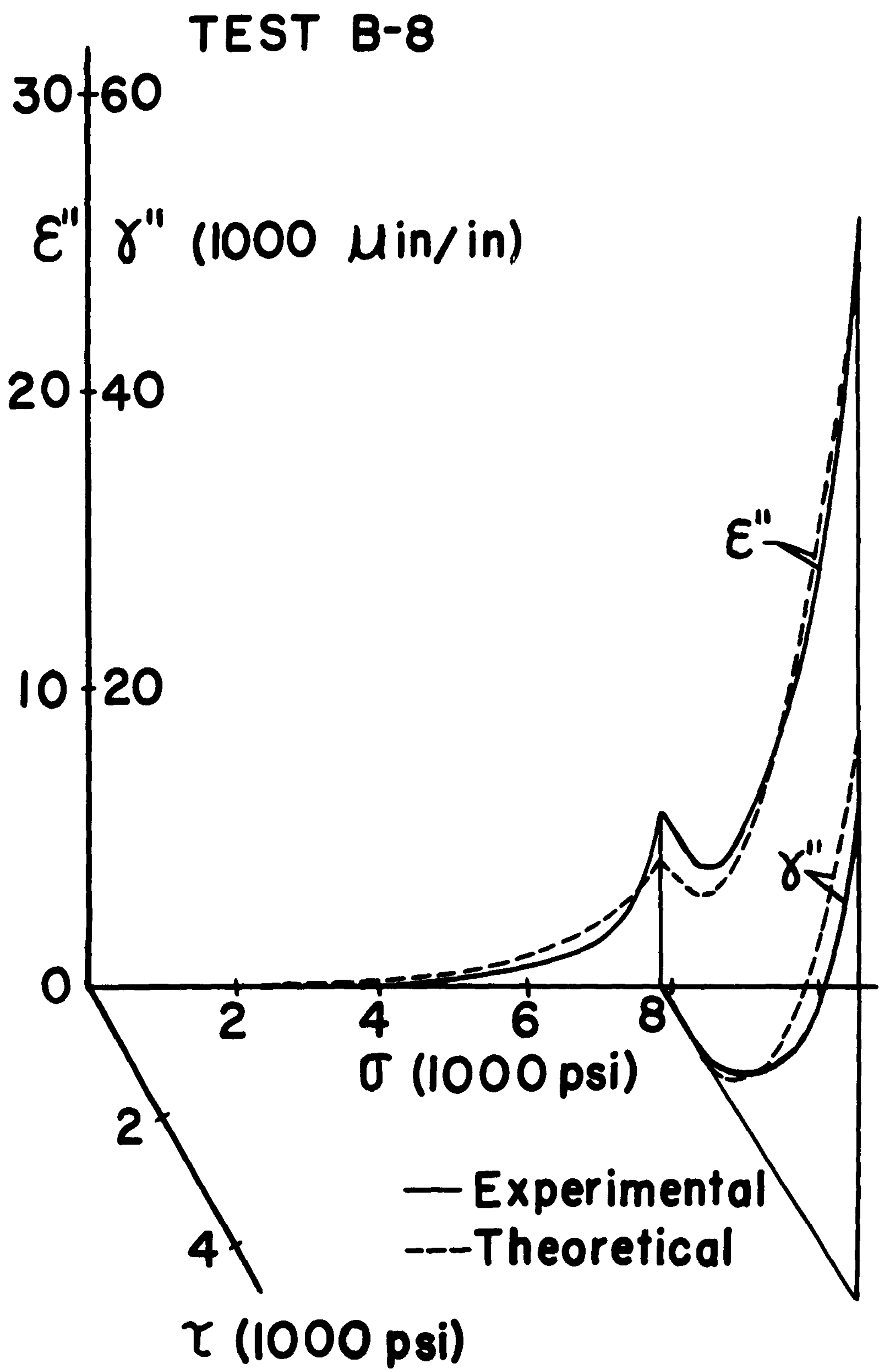

TEST B-8
30 60
ε'' γ'' (1000 μin/in)
20 40
10 20
0
ε''
γ''
2
4
6
8
σ (1000 psi)
2
4
τ (1000 psi)
— Experimental
--- Theoretical

Fig.14

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Attn: Division of Engineering Sciences (1)

Commanding Officer
Squier Signal Laboratory
Fort Monmouth, New Jersey
Attn: Components & Materials Branch (1)

NAVY

Chief of Naval Operations
Department of the Navy
Washington 25, D. C.
Attn: Op 37 (1)

Commandant, Marine Corps
Headquarters, U.S. Marine Corps
Washington 25, D. C. (1)

Chief, Bureau of Ships
Department of the Navy
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Attn: Code 300 (1)
Code 327 (2)
Code 420 (2)
Code 423 (2)
Code 440 (1)
Code 442 (2)
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Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D. C.
Attn: AER-2 (1)
AC (1)
AR-4 (1)
AD (1)
AD-2 (1)
AD-22 (1)
AD-23 (1)
GM (1)
RS-7 (1)
RS-8 (1)
RS-9 (1)
SI (1)
TD-42 (1)

Chief, Bureau of Ordnance
Department of the Navy
Washington 25, D. C.
Attn: Ad3 (1)
Re (1)
Re3 (1)
Re9 (1)
Rex 10 (1)

Chief, Bureau of Yards and Docks
Department of the Navy
Washington 25, D. C.
Attn: Code D-210 (1)
Code D-213 (1)
Code D-220 (1)
Code D-222 (1)
Code D-410 (1)
Code D-410C (1)
Code D-440 (1)
Code D-500 (1)

Commanding Officer and Director
David Taylor Model Basin
Washington 7, D. C.
Attn: Code 142 (1)
Code 700 (1)
Code 720 (1)
Code 730 (1)
Code 740 (1)

Commander
U.S. Naval Ordnance Laboratory
White Oak, Maryland
Attn: Technical Library (2)
Technical Evaluation Department (1)

Director
Materials Laboratory
New York Naval Shipyard
Brooklyn 1, New York (1)

Officer-in-Charge
Naval Civil Engineering Research
and Evaluation Laboratory
U.S. Naval Construction Battalion
Center
Port Hueneme, California (2)

Director
Naval Air Experimental Station
Naval Air Material Center
Naval Base
Philadelphia 12, Pennsylvania
Attn: Materials Laboratory (1)
Structures Laboratory (1)

Officer-in-Charge
Underwater Explosion Research Division
Norfolk Naval Shipyard
Portsmouth, Virginia
Attn: Dr. A. H. Keil (2)

Commander
U.S. Naval Proving Grounds
Dahlgren, Virginia (1)

Superintendent
Naval Gun Factory
Washington 25, D. C. (1)

Commander
Naval Ordnance Test Station
Inyokern, China Lake, California
Attn: Physics Division (1)
Mechanics Branch (1)

Commander
Naval Ordnance Test Station
Underwater Ordnance Division
3202 E. Foothill Boulevard
Pasadena 8, California
Attn: Structures Division (1)

Commanding Officer and Director
Naval Engineering Experiment
Station
Annapolis, Maryland (1)

Superintendent
Naval Post Graduate School
Monterey, California (1)

Commandant
Marine Corps Schools
Quantico, Virginia
Attn: Director, Marine Corps
Development Center (1)

AIR FORCE

Commanding General
U.S. Air Force
Washington 25, D. C.
Attn: Research and Development
Division (1)

Commander
Air Material Command
Wright-Patterson Air Force Base
Dayton, Ohio
Attn: MCREX-B (1)
Structures Division (1)

Commander
U.S. Air Force Institute of Technology
Wright-Patterson Air Force Base
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Attn: Chief, Applied Mechanics Group
(1)

Director of Intelligence
Headquarters, U.S. Air Force
Washington 25, D. C.
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Div.) (1)

Commander
Air Research and Development Command
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PART C: OTHER GOVERNMENT ACTIVITIES

U.S. Atomic Energy Commission
Washington 25, D. C.
Attn: Director of Research (2)

Director
National Bureau of Standards
Washington 25, D. C.
Attn: Division of Mechanics (1)
Engineering Mechanics
Section (1)
Aircraft Structures (1)

Commandant
U.S. Coast Guard
1300 E Street, N.W.
Washington 25, D. C.
Attn: Chief, Testing and
Development Division (1)

U.S. Maritime Administration
General Administration Office Building
Washington 25, D. C.
Attn: Chief, Division of Preliminary
Design (1)

National Advisory Committee for
Aeronautics
1512 H Street, N.W.
Washington 25, D. C.
Attn: Loads and Structures Div. (2)

Director
Langley Aeronautical Laboratory
Langley Field, Virginia
Attn: Structures Division (2)

Director
Forest Products Laboratory
Madison, Wisconsin (1)

Civil Aeronautics Administration
Department of Commerce
Washington 25, D. C.
Attn: Chief, Aircraft Engineering
Division (1)
Chief, Airframe and Equipment
Branch (1)

National Sciences Foundation
1520 H Street, N.W.
Washington 25, D. C.
Attn. Engineering Sciences Div. (1)

National Academy of Science
2101 Constitution Avenue
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Attn: Technical Director, Committee
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Executive Secretary, Committee
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Project Staff (10)

For your future distribution (10)